08/470424

DESCRIPTION

FUEL ASSEMBLY AND NUCLEAR REACTOR

Technical Field

The present invention relates to a fuel assembly,
5   and more particularly to a fuel assembly which can be
used in a boiling-water reactor to save the consumption
of nuclear fuel substances.

Background Art

In a conventional boiling-water reactor as is
10 disclosed in Japanese Patent Laid-Open No. 121389/
1979, the reactor core is loaded with a fuel assembly
which has a pipe (hereinafter referred to as water
rod) in which the cooling water only flows to
decelerate the neutrons. Under the operation
15 conditions of the conventional boiling-water reactor,
the water rod exhibits an increased reactivity with
the increase in the number of hydrogen atoms for
uranium atoms, enabling the nuclear fuel substances
loaded in the reactor core to be effectively utilized.

20 In order to more effectively use the nuclear
fuel substances, furthermore, it is recommended to
change the number of hydrogen atoms in the reactor
core as the nuclear fuel substances burn.

Japanese Patent Laid-Open Nos. 125390/1982 and
25 125391/1982 teach one of the methods. That is,
according to these patent publications, provision
is made of slow neutron-absorbing water purge rods
and intermediate neutron-absorbing water purge rods
constituted by a stainless steel which has a larger
30 reactivity value than that of the above water purge
rods, and the amount of the cooling water in the
reactor core is adjusted by controlling the amount
for inserting the water purge rods in the reactor
core. The water purge rods serve as means for
35 changing the number of hydrogen atoms in the reactor

core. The amount of the cooling water in the reactor
core decreases with the increase in the amount for
inserting the water purge rods in the reactor core,
and the amount of the cooling water increases in the
5 reactor core with the decrease in the amount of
insertion. According to the above-mentioned method,
water purge rods of different kinds must be newly
provided and must be operated by drive means,
requiring complex structure and cumbersome operation.

10 Japanese Patent Laid-Open No. 38589/1986 discloses
a fuel assembly which employs static means in order
to solve the above-mentioned problems. According
to this patent publication, the number of hydrogen
atoms is changed by providing fuel rods having a
15 low uranium 235 concentration in the water rod of
fuel assembly, and by utilizing the change in the
amount of voids in the water rod before and after
uranium 235 of the fuel rods extinguishes.

There is a method of adjusting the amount of
20 the cooling water that flows in the reactor core
without the need of newly providing operation means
such as water purge rods. That is, the cooling
water is permitted to flow in small amounts in the
reactor core during the start of the fuel cycle,
25 and is then permitted to flow in increased amounts
as the fuel cycle proceeds halfway.

Advantages will now be described in the case
when the number of hydrogen atoms is changed in
the reactor core accompanying the burn of the nuclear
30 fuel substances.

In the case of a typical fuel assembly used for
boiling-water reactors, a higher burning degree can
be obtained when the operation is carried out at a
high void fraction (void fraction, 50%) during the
35 period of a burning degree of 0 to 30 GWD/T and when

the operation is carried out at a decreased void
fraction (void fraction, 30%) during the period of
a burning degree of 30 to 40 GWD/T than when the
operation is carried out at a constant void fraction
5   (e.g., at a void fraction of 30%).

　　　This is because, the neutrons have a high average
speed and are easily absorbed by uranium 238 when
the void fraction is high and the ratio of the number
of hydrogen atoms to the number of uranium atoms is
10   small, i.e., when the number of hydrogen atoms is
small. The nuclear fuel substances used in the
boiling-water reactor contains uranium 235 and
uranium 238, uranium 235 occupying several per cent
of the whole nuclear fuel substances and uranium
15   238 occupying most of the nuclear fuel substances.
Among them, uranium 235 absorbs the neutrons and
develops chiefly the nuclear fission, but uranium
238 develops nuclear fission very little. Therefore,
the burn-up decreases if uranium 235 burns and
20   decreases.

　　　Uranium 238, however, is converted into plutonium
239 when it absorbes neutrons of a large energy
produced by the nuclear fission. Like uranium 235,
however, plutonium 239 absorbs decelerated thermal
25   neutrons to develop nuclear fission. The higher
the void fraction, the larger the energy of the
neutrons and uranium 238 is converted into plutonium
239 at an increased ratio, while suppressing the
nuclear fission of uranium 235 and plutonium 239.
30   Therefore, the higher the void fraction, the slower
the rate of reduction of the total amount of uranium
235 and plutonium 239.

　　　A high void fraction, however, causes the
absolute value of reactivity to decrease. If the
35   void fraction is maintained high, therefore, a

minimum level is reached quickly at which the
reactivity maintains the criticality compared with
when the void fraction is low. Therefore, if the
void fraction is lowered at that moment, the neutrons
5   exhibit increased deceleration effect, whereby nuclear
fission of uranium 235 and plutonium 239 increases,
so that good reactivity is obtained compared with
when the fuel substances are burned at a high void
fraction that is maintained constant. This makes it
10   possible to burn the core material contained in the
nuclear fuel substances for an extended period of
time before a minimum reactivity necessary for the
criticality is reached.

In the foregoing was mentioned the principle
15   which is called spectrum shift operation for
effectively utilizing the nuclear fuel substances
by changing the void fraction accompanying the burn
of the core material.

Neither the method which provides static means
20   in a simply constructed water rod nor the method
which changes the number of hydrogen atoms in the
reactor core by changing the amount of the cooling
water (called reactor core flow rate) which flows
through the reactor core, makes it possible to widely
25   change the void fraction in the reactor core; i.e.,
these methods can only give small effect in the
practical nuclear reactors.

That is, the lower limit of the flow rate in
the reactor core is determined by the thermal limit,
30   and the upper limit is determined by the capacity
of the circulation pump and the flow-induced
vibration. Under the condition where the boiling-
water reactor is producing a rated thermal output,
therefore, it is allowed to change the void fraction
35   only within a narrow range with the rated 100% flow

rate in the reactor core as a center. For example,
if the flow rate in the reactor core is allowed to
change over a range of from 80 to 120%, then the void
fraction can be changed by about 9%.

5   Even with the structure in which a heat generating
member (nuclear fuel substance) of which the calorific
power decreases accompanying the burn, is placed in
the water rod as disclosed in Japanese Patent Laid-
Open No. 38589/1986, the void fraction in the water

10   rod changes by about 30% at the greatest. The water
in the water rod does not contribute to the colling,
and it is not allowed to much increase the sectional
area of the water rod in the fuel assembly. If it
is presumed that the sectional area of the water rod

15   occupies 30% of the cooling water path in the fuel
assembly, the effective void fraction change of 30%
becomes 9% (30% x 0.3) if it is regarded as the whole
fuel assembly. Further, since a fuel rod having a
low enrichment is used as a heat generating member,

20   the structure becomes complex and its production
involves cumbersome operation.

     To achieve a wide range of void fraction change,
the flow rate in the water rod should be changed
extremely greatly or the calorific power of the

25   nuclear fuel substance in the water rod should be
changed greatly. In fact, however, the flow rate or
the calorific power cannot be greatly changed without
employing the moving portions. Provision of the
moving portions, however, poses problems from the

30   standpoint of reliability and makes the mechanism
complex.
Disclosure of Invention

     The object of the present invention is to provide
a fuel assembly which is simply constructed and which

35   is capable of greatly changing the internal average

void fraction.

The aforementioned object is achieved by the provision of a resistance member at the lower end portion of the fuel assembly; a coolant ascending
5   path in which the water rods have coolant inlet ports that are open in a region lower than the resistance member; and a coolant descending path which is communicated with the coolant ascending path and which has a coolant delivery port that is open in a region
10   higher than the resistance member, in order to guide the coolant downwardly which is opposite to the direction in which the coolant flows in the coolant ascending path.

As the flow rate of the coolant that passes
15   through the reactor core decreases, the coolant descending path of the water rod is filled with water vapor and as the flow rate of the coolant increases, the amount of water vapor decreases conspicuously in the coolant descending path. Therefore, the reactivity
20   can be increased toward the last period of fuel cycle.
Brief Description of Drawings

Fig. 1 is a diagram which illustrates the principle of a water rod used in the present invention;

Fig. 2 is a diagram which schematically shows
25   pressure differential characteristics that develop across the outlet and the inlet of the water rod of Fig. 12;

Figs. 3A, 3B and 3C are diagrams illustrating the flow conditions in the water rod at points S, T
30   and U of Fig. 2;

Fig. 4 is a vertical section view of a fuel assembly according to a preferred embodiment of the present invention;

Fig. 5 is a partial section view of a fuel rod
35   shown in Fig. 4;

Fig. 6 is a section view along a line III-III of Fig. 4;

Fig. 7A is a local vertical section view of the water rod of Fig. 4;

Fig. 7B is a section view along a line IV-IV of Fig. 7A;

Fig. 8 is a diagram illustrating a relationship between the reactor core flow rate and the average void fraction in the reactor core;

Figs. 9, 11 and 13 are diagrams illustrating relationships between the pressure differential across the outlet and the inlet of the water rod and the flow rate of cooling water supplied into the water rods having inner tubes of dissimilar sizes;

Figs. 10, 12 and 14 are diagrams illustrating relationships between the average void fraction in the water rod and the flow rate of cooling water supplied into the water rods that correspond to Figs. 9, 11 and 13;

Fig. 15 is a diagram illustrating a relationship between the average void fraction in the water rod and the pressure differential across the outlet and the inlet of the water rod;

Fig. 16 is a lateral section view of the fuel assembly according to another embodiment of the present invention;

Fig. 17 is a diagram illustrating changes in the amount of core material in the nuclear fuel material for a fuel cycle of the fuel assembly of Fig. 16, average surplus reactivity in the core, ratio of hydrogen atom density to uranium atom density, and flow rate in the reactor core;

Figs. 18A, 20 and 24 are vertical section views of water rods according to further embodiments;

Fig. 18B is a section view along a line A_1-A_1 of

Fig. 18A;

Figs. 19 and 23 are side views of the water rods according to further embodiments;

Figs. 21 and 22 are lateral section views of the water rods according to still further embodiments;

Fig. 25 is a vertical section view of the fuel assembly according to yet further embodiment of the present invention;

Fig. 26 is a local plan view of the orifice of Fig. 25;

Fig. 27 is a section view along a line X_1-X_1 of Fig. 26;

Fig. 28 is a diagram showing a relationship between the Reynolds number and the orifice fraction for an orifice that is smaller than the orifice shown in Fig. 26;

Fig. 29 is a diagram showing a relationship between the flow rate in the reactor core and the output of the nuclear reactor;

Fig. 30 is a diagram illustrating the change in the pressure differential inside and outside the water rod;

Fig. 31 is a diagram showing a relationship between the average void fraction in the water rod and the pressure differential across the outlet and the inlet of the water rod that has an outer tube with an inner diameter of 20 mm and an inner tube with an inner diameter of 12 mm;

Fig. 32 is a vertical section view of a fuel assembly according to a further embodiment of the present invention; and

Fig. 33 is a local vertical section view of a boiling-water reactor in which the fuel assembly of Fig. 1 is loaded.

Best Mode for Carrying Out the Invention

The principle of the present invention will first be described prior to illustrating embodiments of the present invention. Fig. 1 illustrates the structure. Fundamentally, the fuel assembly is provided with a water rod 1 which has a coolant ascending path 2 of which a coolant inlet port 4 is open in a region lower than a resistance member (such as tie plate) 6 provided at a lower portion of the fuel assembly, and which further has a coolant descending path 3 that downwardly guides the coolant from the coolant ascending path and that has a coolant delivery port 5 open in a region higher than the resistance member 6. The resistance member 6 has a plurality of coolant passage ports 7.

The pressure differential ΔP changes between the region lower than the resistance member 6 and the region higher than the resistance member 6 depending upon the change in the flow rate of the coolant (cooling water) that flows through the coolant passage ports 7 formed in the resistance member 6. The pressure differential caused by vena contracta and increase of resistance varies nearly in proportion to the square power of the flow rate of the cooling water. Therefore, if the flow rate of the cooling water passing through the resistance body 6 changes from 80% to 120%, the pressure differential ΔP increases by about 2.25 times.

Fig. 2 illustrates a relationship between the flow rate of cooling water in the water rod 1 and the pressure differential between the inlet and the outlet of the water rod 1 (pressure differential between the coolant inlet port 4 and the coolant delivery port 5). If the flow rate of the cooling water is increased starting from zero, the pressure differential between the outlet and the inlet of the water rod 1 once reaches a maximum value. As the flow rate of the cooling water is further increased, the pressure differential between

the outlet and the inlet of the water rod 1 once drops
to a minimum value, and then increases monotonously.
This is due to the phenomenon shown in Figs. 3A to 3C.

Fig. 3A shows the condition in the water rod 1 at
a point S in Fig. 2, Fig. 3B shows the condition in
the water rod 1 at a point T in Fig. 2, and Fig. 3C
shows the condition in the water rod 1 at a point U in
Fig. 2.

Being irradiated with neutrons and gamma rays
from the fuel rods around the water rod 1, the cooling
water in the water rod 1 generates the heat at a rate
of about 0.5 to 2 W/cm^2. When the flow rate of the
cooling water flowing through the water rod 1 is very
small (condition of point S in Fig. 2), the cooling
water in the water rod 1 generates the heat and
evaporates being irradiated with neutrons and the like.
The upper portions of the coolant ascending path 2
and the coolant descending path 3 are then filled with
the vapor as shown in Fig. 3A. A liquid level L_1 is
established in the coolant ascending path 2, and the
pressure differential between the outlet and the inlet
of the water rod 1 is generated by the difference in
the static water head between the liquid level L_1 and
the liquid level L_2 of the coolant delivery port 5
(outlet of the coolant descending path 3) of the water
rod 1. The flow rate of the cooling water that flows
into the coolant ascending path 2 maintains balance
with respect to the flow rate by which the vapor flows
out through the coolant delivery port 5.

As the flow rate of the cooling water is further
increased from the point S in Fig. 2, the cooling water
flows into the coolant ascending path 2 at a rate that
is greater than the amount by which the cooling water
is vaporized. In such a case (e.g., at the point T
in Fig. 2), the cooling water flows down through the

coolant descending path 3 as shown in Fig. 3B. At
this moment, the static head in the coolant ascending
path 2 is partly cancelled by the weight of the
cooling water that flows through the coolant descending
5   path 3, and the pressure differential between the
outlet and the inlet of the water rod 1 becomes
smaller than the maximum value S_0. As the flow rate
of the cooling water further increases, however, the
unsaturated water introduced through the coolant inlet
10   port 4 is not boiled in the coolant ascending path 2
and the coolant descending path 3 (void fraction is
very reduced), and is permitted to flow out through
the coolant delivery port 5 (condition of point U in
Fig. 2, Fig. 3C). Therefore, the water flows through
15   the coolant ascending path 2 and the coolant descending
path 3 almost in the form of a single phase stream.
Under the condition of Fig. 3A, therefore, the static
water heads at the level of the coolant ascending
path 2 and at the level of the coolant delivery port
20   5 in the coolant descending path 3 are cancelled by
each other, so that the difference in the static
water head becomes very small. However, since the
cooling water flows at a large rate in the water rod
1, the pressure loss increases due to friction and
25   inversion in the flow of the cooling water, and the
pressure differential increases again between the
outlet and the inlet of the water rod 1.

Owing to the above-mentioned phenomenon, the
flow rate of the cooling water in the water rod 1
30   varies greatly and the void fraction varies greatly
even though the pressure differential varies little
between the outlet port and the inlet port of the
water rod 1.

Therefore, the void fraction can be changed
35   greatly by changing the flow rate of the cooling

water (flow rate in the reactor core) that flows in
the fuel assembly, if the resistance of the resistance
member 6 is so adjusted that the pressure differential
between the outlet and the inlet of the water rod 1
5   is smaller than a pressure differential between the
outlet and the inlet of the water rod 1 that corresponds
to the minimum value T_0 of Fig. 2 when the flow rate
in the reactor core is 80% and that the pressure
differential between the outlet and the inlet of the
10 water rod 1 is in excess of a pressure differential
between the outlet and the inlet of the water rod 1
that corresponds to the maximum value S_0 of Fig. 2
when the flow rate in the reactor core is 120%.   In
the above example, the flow rate of 80% in the
15 reactor core lies on the left side of the maximum
value S_0 and, preferably, lies on the left side of
a point Q (pressure differential between the outlet
and the inlet same as the minimum value T_0) in Fig.
2, and the flow rate of 120% in the reactor core
20 lies on the right side of the minimum value T_0 and,
preferably, lies on the right side of the point R
(pressure differential between the outlet and the
inlet same as the maximum value S_0) in Fig. 2.

A preferred embodiment of the invention utilizing
25 the above-mentioned principle, i.e., a fuel assembly
to be used in a boiling-water reactor, will now be
described in conjunction with Figs. 4, 5, 6, 7A and
7B.

A fuel assembly 10 of this embodiment is comprised
30 of fuel rods 11, an upper tie plate 12, a lower tie
plate 13, a fuel spacer 16, a channel box 17, and a
water rod 18. The upper and lower ends of the fuel
rods 11 are held by the upper tie plate 12 and the
lower tie plate 13. The water rod 19, too, is held
35 at its both ends by the upper tie plate 12 and the

lower tie plate 13. Several fuel spacers 16 are
arranged in the axial direction of the fuel assembly
10 to maintain an appropriate distance among the
fuel rods 11. The fuel spacers 16 are held by the
5   water rod 19. The channel box 17 is mounted on the
upper tie plate 12 to surround the outer periphery
of a bundle of fuel rods 11 that are held by the
fuel spacers 16. The lower tie plate 13 has a fuel
rod supporting portion 14 at the upper end and has
10   space 15 under the fuel rod supporting portion 14.
The lower ends of the fuel rods 11 and the water
rod 19 are supported by the fuel rod supporting
portion 14. With reference to Fig. 5, a number of
fuel pellets 33 are loaded in a covering tube 30
15   whose both ends are sealed with an upper end plug
31 and a lower end plug 32. A gas plenum 34 is
formed at an upper end of the covering tube 30. The
water rod 19 has a diameter (outer diameter of an
outer tube 21 that will be mentioned later) which
20   is greater than the diameter of the fuel rod 11, and
is arranged at the central portion in the cross
section of the fuel assembly 10.

Structure of the water rod 19 will now be described
in detail with reference to Figs. 7A and 7B. The
25   water rod 19 consists of an inner tube 20, an outer
tube 21 and a spacer 22. The outer tube 21 and the
inner tube 20 are arranged in concentric with each
other, and the outer tube 21 surrounds the outer
periphery of the inner tube 20. The upper end of
30   the outer tube 21 is sealed with a covering portion
23, and the upper end of the covering portion 23 is
held by the upper tie plate 12 being inserted therein.
The covering portion 23 covers the upper end of the
inner tube 20 so as to form a gap with respect to
35   the upper end of the inner tube 20. The upper rod

of the inner tube 20 is secured to the inner surface
of the outer tube 21 via plate-like spacers 22 that
are radially arranged from the axis of the water rod
19. The lower end of the outer tube 21 is sealed
5   with a sealing portion 24. The lower end of the
inner tube 20 penetrates through the sealing portion
24 to protrude downwardly. The lower end of the
inner tube 20 penetrates through the fuel rod
supporting portion 14 of the lower tie plate 13.
10   A coolant inlet port 28 formed in the lower end of
the inner tube 20 is open in the space 15 of the
lower tie plate 13. The interior of the inner tube
20 forms a coolant ascending path 25. An annular
path formed between the inner tube 20 and the outer
15   tube 21 defines a coolant descending path 26. A
plurality of cooling water delivery ports 29 are
formed in the wall at the lower end of the outer
tube 21 in the circumferential direction. The cooling
water delivery ports 29 are formed in the circumferential
20   direction maintaining an equal distance and are open
in a region over the fuel rod supporting portion 14.
In this embodiment, the fuel rod supporting portion
14 exhibits the function of the resistance member 6
of Fig. 12. The cooling water ascending path 25 and
25   the cooling water descending path 26 are communicated
with each other through an inverting portion 27 formed
at an upper end of the water rod 19. Thus, the water
rod 19 contains therein a cooling water path of an
inverted U-shape which consists of the cooling water
30   ascending path 25, the cooling water descending path
26 and the inverting portion 27.
     When the fuel assembly 1 of this embodiment is
loaded in the reactor core of the boiling-water reactor
(the whole fuel assemblies are represented by the fuel
35   assemblies 1) to operate the boiling-water reactor,

most of the cooling water is directly introduced into
space among the fuel rods 11 of the fuel assembly 10
loaded in the reactor core passing through space 15
of the lower tie plate 13 and penetration holes 18

5   (Fig. 6) formed in the fuel rod supporting portion
14.   The remainder of the cooling water that flew
into space of the lower tie plate 13 flows through
the coolant inlet port 28 into the coolant ascending
path 25 of the water rod 19, and is delivered into

10   the region over the fuel rod supporting portion 14
through the inverting portion 27, the coolant
descending path 26 and the coolant delivery ports 29.
The cooling water delivered from the cooling water
delivery ports 29 may be in the form of a liquid or

15   a gas (vapor) depending upon the flow rate of the
cooling water that flows into the water rod 19
through the cooling water inlet port 28 as described
earlier.   According to this embodiment, the pressure
loss by the fuel rod supporting portion 14 and the

20   specifications of the inner tube 20 and the outer tube
21 have been selected in advance, so that the condition
of Fig. 3A develops in the water rod 19 when the flow
rate in the reactor core is smaller than 100% (flow
rate at the maximum value S_0 of Fig. 2 in the water

25   rod 19), and the condition of Fig. 3C develops in
the water rod 19 when the flow rate in the reactor
core is 110% (flow rate at the point R of Fig. 2 in
the water rod 19).

Concretely described below is how to operate the

30   boiling-water reactor while changing the void fraction
in the water rod 19 under the condition where the
fuel assembly 10 is loaded in the reactor core of the
boiling-water reactor.   This operation method applies
for one fuel cycle (operation period of a nuclear

35   reactor from when the fuel in the reactor core is

replaced and operation of the nuclear reactor is
started to when the nuclear reactor is stopped for
renewing the fuel, i.e., usually, one year).

In the boiling-water reactor as disclosed in
5   Japanese Patent Publication No. 11038/1982, Col. 8,
line 19 to Col. 10, line 31, the control rods are
operated and the flow rate in the reactor core is
adjusted to raise the atomic output up to 100% (point
N in Fig. 7 of the above publication and 80% flow
10   rate in the reactor core in this embodiment) in order
to prevent the fuel from breaking. The flow rate in
the reactor core is increased to compensate the
reduction of reactor output as the nuclear fuel
substance is consumed, i.e., to maintain the reactor
15   output at 100%. When the flow rate in the reactor
core has reached 100% owing to the compensation
operation, the flow rate in the reactor core is
decreased to 20% and the control rods are pulled out
until the nuclear reactor produces a predetermined
20   output as disclosed in Japanese Patent Publication
No. 11038/1982, Col. 11, line 23 to Col. 12, line 40
(Col. 9, line 47 to Col. 10, line 51 of U.S.P.
4,279,698). Thereafter, the flow rate in the reactor
core is increased to 80% to maintain the reactor
25   output at 100%. To maintain the reactor output at
100%, the control operation is repeated.

According to this embodiment, the output of the
nuclear assembly is flattened in the axial direction
by utilizing nuclear characteristics. After the
30   flow rate in the reactor core has been decreased,
therefore, the control rods are pulled out; i.e.,
there is no need of pulling out the control rods or
there is no need of inserting other control rods
unlike the art disclosed in Japanese Patent
35   Publication No. 11038/1982 Col. 12, lines 19 to 29

(U.S.P. 4,279,698, Col. 10, lines 21 to 34), and
what is needed is to pull out only those control
rods that are deeply inserted. As described above,
the operation for obtaining 100% of reactor output
5   with the flow rate in the reactor core of smaller than
100% is continued for about 70% of a fuel cycle period.
During the period of about 70%, the water rod 19 in
the fuel assembly 1 assumes the condition as shown
in Fig. 3A. That is, the upper portion of the coolant
10 ascending path 25 and the interior of the coolant
descending path 26 are filled with the vapor; i.e.,
the liquid cooling water does not almost exist in
the vapor region which is formed in the water rod 19
in the fuel assembly 1 loaded in the reactor core.
15 Therefore, up to 70% of the fuel cycle, the vapor
region is formed in the water rod 19, and the cooling
water in the reactor core is partly expelled.

It can be said that the fuel assembly 10 according
to this embodiment is provided with a water rod that
20 has a vapor reservoir. The coolant descending path
26 works as a vapor reservoir until the flow rate
in the reactor core exceeds 100% as will be described
later. Formation of the vapor region in the water
rod 19 suppresses the effect for decelerating neutrons
25 and promotes the conversion of uranium 238 into
plutonium 239 in the nuclear fuel substance.
Suppression of the neutron deceleration effect results
in the suppression of nuclear fission such as of
uranium 235 and results in the decrease in the
30 reactivity. Decrease in the reactivity, however,
can be alleviated by pulling out the control rods by
an increased amount. During this period, new core
materials such as plutonium 239 and the like may be
formed, and the core material in the reactor core
35 decreases at a reduced rate. According to this

embodiment as described above, the surplus reactivity
(surplus neutrons) is absorbed by uranium 238 in the
nuclear fuel substances to form a new core material.

By the time when the operation period of the

5   boiling-water reactor reaches about 70% of the fuel
cycle, the surplus reactivity in the reactor core
will have been lowered to a minimum level for
maintaining the criticality. In this case, the flow
rate in the reactor core is gradually increased in

10   excess of 100%; i.e., the flow rate in the reactor
core is increased to 120% at the time when the
operation of a fuel cycle is stopped. The recirculation
pump does not hinder the operation at all if the flow
rate in the reactor core does not exceed 120%. The

15   output of the nuclear reactor is maintained at 100%
from when the flow rate in the reactor core exceeds
100% until when it reaches 120%. When the flow rate
in the reactor core is greater than 110%, the interior
of the water rod 19 assumes the condition of Fig. 3C

20   where the liquid flows in the form of a single-phase
stream and no vapor stays in the coolant descending
path 26. As the flow rate in the reactor core becomes
greater than 110%, therefore, the amount of cooling
water (the number of hydrogen atoms) in the reactor

25   core increases remarkably compared with when the
flow rate in the reactor core is smaller than 100%,
and whereby the effect increases for decelerating
the neutrons, and hence nuclear fission of uranium
235 and the like becomes active. Accordingly, the

30   infinite multiplication factor of the fuel assembly
increases and it is made possible to effectively
utilize the core materials.

The fuel assembly 1 experiences the fuel cycle
operation four times in the reactor core. Therefore,

35   the conditions of Fig. 3A and 3B are alternatingly

repeated four times each.

According to the fuel assembly 10 of this
embodiment as described above, the water rod is made
up of a simply constructed double tube. Therefore,
5   the phase condition of the cooling water in at least
the coolant descending path 26 can be successively
changed from the gaseous state to the liquid state
by means which controls the output of the nuclear
reactor (by means which adjusts the flow rate in the
10   reactor core and which may be a recirculation pump).
That is, the range in which the average void fraction
changes in the fuel assembly 10 can be greatly
broadened being added up with the range of void
fraction change due to the water rod 19. Concretely
15   speaking, the flow rate in the reactor core in this
embodiment is increased to 80 to 120%, so that the
average void fraction of the fuel assembly 10 changes
as shown in Fig. 8. This is due to the change of
void fraction outside the water rod 19. The fuel
20   assembly 10 exhibits an average void fraction change
on which is superposed an average void fraction
change produced by the water rod 19. Therefore, the
nuclear fuel substances can be effectively utilized
with a simply constructed structure, and the operation
25   period of a fuel cycle can be greatly extended.

Described below is another operation control
to substitute for the aforementioned operation control.
According to Japanese Patent Publication No. 44237/
1983 (U.S.P. 4,285,769), a fuel cell constituted by
30   four adjoining fuel assemblies is divided into a
controlled cell and a noncontrolled cell, the average
enrichment of the controlled cell is selected to be
smaller than that of the noncontrolled cell, and the
output of the nuclear reactor under the ordinary
35   operation condition is controlled by the control rods

only that are inserted in the controlled cell. On
Col. 27, line 29 to Col. 28, line 43 of Japanese
Patent Publication No. 44237/1983 (U.S.P. 4,285,769,
Col. 16, lines 6 to 65), there is described that the
5   control rods inserted in the controlled cell (c cell)
are driven by a control rod driving device of the
type of fine movement. After the boiling-water
reactor is started, the control rods in the controlled
cell and the flow rate in the reactor core are
10   adjusted to maintain 100% output of the nuclear reactor
with a 80% flow rate in the reactor core. Reduction
of the reactor output due to the consumption of the
core material is compensated by increasing the flow
rate in the core before the flow rate in the core
15   reaches 100% and after the flow rate has reached 100%,
by gradually pulling out the control rods from the
controlled cell by the control rod drive device while
maintaining the flow rate in the reactor core at 100%.
After 70% period of the fuel cycle, operation of the
20   control rods is stopped and the flow rate in the
reactor core is gradually increased up to 120%.
During the period of up to 70% of the fuel cycle,
the water rod 19 is filled with the water vapor as
mentioned earlier and after 70% of the fuel cycle,
25   the void fraction in the water rod 19 can be markedly
reduced.

       In the aforementioned embodiment, the inverting
portion 27 is arranged at a position over the position
of a gas plenum 34 of the fuel rod 11, i.e., over the
30   upper end of the fuel pellet-filled region. The lower
end of the coolant descending path 26 is located at
a position at least under the upper end (lower end
of gas plenum 34) of the fuel pellet-filled region
(region filled with fuel pellets 33) of the fuel
35   assembly 1. In other words, the vapor reservoir of

the water rod 19 should be located at a position at
least lower than the upper end of the fuel pellet-
filled region of the fuel assembly. In particular,
in order that the vapor region is uniformly distributed
5   in the axial direction of the fuel pellet-filled
region where nuclear fission takes place in the
nuclear assembly, the cooling water delivery ports
29 (or vapor delivery ports of the vapor reservoir)
of the coolant descending path 26 (vapor reservoir)
10   should be located near the lower end of the fuel
pellet-filled region or desirably at a position
(near the fuel rod supporting portion 14) under the
fuel pellet-filled region. Namely, the vapor region
under the condition of Fig. 3A is formed over the
15   full length in the axial direction of the fuel
pellet-filled region, and the output distribution
of the fuel assembly 1 is flattened in the axial
direction.

      In this embodiment in which the coolant descending
20   path 26 surrounds the periphery of the coolant
ascending path 25, the neutron deceleration effect
of when the coolant ascending path 25 and the coolant
descending path 26 are substantially filled with
liquid cooling water and the effect of converting
25   into plutonium of at least when the coolant descending
path 26 is filled with the vapor, can be uniformly
imparted to the fuel rods that surround the water
rod 19.

      By lowering the position of the inverting portion
30   27 from the upper end of the fuel pellet-filled region,
furthermore, there can be employed a short water rod
19 having a length shorter than the fuel rods 11.
In this case, pressure loss in the fuel assembly can
be decreased.

35   Referring to Fig. 2, difference in the flow rates

in the reactor core between the maximum value S_0 and
the minimum value T_0, pressure differential between
the outlet and the inlet of the water rod 19 for the
maximum value S_0, and pressure differential between
the outlet and the inlet of the water rod 19 for the
minimum value T_0, undergo the change depending upon
the sizes of the inner tube 20 and the outer tube 21.
This will now be described.

Figs. 9, 11 and 13 illustrate changes of pressure
differential between the outlet and the inlet of the
water rod 19 for the flow rate of cooling water
supplied into the water rod 19 when the outer tube
21 has an inner diameter of 30 mm and when the inner
diameter and outer diameter of the inner tube 20 are
changed. Fig. 9 shows the characteristics when the
inner tube 20 has an outer diameter of 14 mm and an
inner diameter of 12 mm, Fig. 11 shows the character-
istics when the inner tube 20 has an outer diameter
of 17 mm and an inner diameter of 15 mm, and Fig. 13
shows the characteristics when the inner tube 20 has
an outer diameter of 20 mm and an inner diameter of
18 mm. Figs. 10, 12 and 14 illustrate changes of
the average void fraction in the water rod for the
flow rate of cooling water supplied into the water
rod, that correspond to Figs. 9, 11 and 13.

When the inner tube 20 is thin as will be obvious
from Fig. 9, a maximum value is reached with a flow
rate of cooling water which is greater than that of
the thick inner tube 20 (Figs. 11 and 13), and the
pressure differential thereafter changes suddenly.
Therefore, the range for changing the flow rate of
the cooling water is small compared with the range
for changing the pressure differential. This is due
to the fact that since the inner tube 21 is thin,
the heat is generated in small amounts in the inner

tube 20 and the flow rate of the cooling water
decreases, that surpasses the amount of vapor
generated in the inner tube 20, and that the fluid
flows through the inner tube 20 at such a high speed
5   that the flow resistance increases. When the
sectional area of the coolant descending path 26
between the inner tube 20 and the outer tube 21 is
great and the flow rate is small, however, the void
is almost 100% in the coolant descending path 26.
10   Therefore, the range in which will change the average
void fraction of the water rod having a thin inner
tube 20 is little different from that of the water
rod having a thick inner tube 20. On the other hand,
the thicker the inner tube 20 of the water rod, the
15   smaller the variable range of the pressure differential
relative to the variable range of the cooling water.
In any case, however, the average void fraction
decreases sharply as a maximum value of the pressure
differential is exceeded as will be obvious from
20   Figs. 10, 12 and 14. Referring to Figs. 9, 11 and
13, furthermore, the average void fraction in the
water rod for the flow rate of cooling water greater
than a point R is conspicuously smaller than the
average void fraction for the flow rate of cooling
25   water smaller than the maximum value S_0.
        Fig. 15 illustrates a relationship between the
average void fraction in the water rod 19 and the
pressure differential between the outlet and the
inlet of the water rod 19, such that the contents of
30   Figs. 9 to 14 can be easily comprehended. As will
be obvious from Fig. 15, the average void fraction
of the water rod drops from 76% to 2% when the
pressure differential is changed from 0.015 MPa to
0.03 MPa between the outlet and the inlet of the
35   water rod 19 which employs the inner tube having an

outer diameter of 20 mm. The pressure loss of the
fuel rod supporting portion 14 of the lower tie plate
2 varies nearly in proportion to the square power of
the flow rate of cooling water that flows in the fuel
5   assembly 1 as mentioned earlier. Therefore, if the
pressure differential between the outlet and the inlet
of the water rod is set to be 0.015 MPa when the flow
rate of cooling water that flows through the fuel
assembly 1 is 80%, the pressure differential becomes
10 0.034 MPa when the flow rate of cooling water is
120%, and the average void fraction becomes 1% in
the water rod. Therefore, the variable range of
average void fraction in the water rod 19 is 75%;
i.e., the variable range of average void fraction
15 is 7.5% with the fuel assembly 10 as an average.
Accordingly, a net variable range of average void
fraction of the fuel assembly 10 is 16.5% being added
up with 9% by the flow rate in the reactor core of
Fig. 8.
20   As shown in Fig. 6, the water rod 19 occupies
about one-tenth the sectional area of the coolant
path of the fuel assembly 10. Here, the variable
range of average void fraction of the fuel assembly
can be increased by providing two or more water rods
25 19 in the fuel assembly. To improve fuel economy,
there has been proposed a fuel assembly which is
provided with nine water rods. In this case, the
water rods as a whole occupy about 30% the sectional
area of the coolant path of the fuel assembly. A fuel
30 assembly 35 of this embodiment is shown in Fig. 16.
The fuel assembly 35 is the one in which the water
rods of the fuel assembly disclosed in Japanese
Patent Application No. 167972/1986, page 9, line 4
to page 11, line 5, and Fig. 1 are all replaced by
35 the above-mentioned water rods 19. The fuel assembly

35 of this embodiment further exhibits the effect of
the fuel assembly 1 of Japanese Patent Application
No. 167972/1986 (effect of reactivity gain shown in
Fig. 3 of this prior application).

5   Described below is the operation of the boiling-
water reactor in which the fuel assembly 35 of this
embodiment is loaded in the reactor core. The whole
fuel assemblies in the reactor core is represented
by the fuel assembly 35. Fig. 16 illustrates the

10   change of characteristics of the case when the
boiling-water reactor loaded with the fuel assembly
35 is operated with two continuous fuel cycles.
Broken lines indicate the case of this embodiment
and solid lines indicate the case when use is made

15   of the fuel assembly 35 which has conventional rods
19 (without coolant descending path 26). In the
former case, the spectrum shift operation is carried
out while changing the void fraction and in the latter
case, no spectrum shift operation is carried out.

20   The output of the nuclear reactor during the fuel
cycle period is controlled by using the method
disclosed in Japanese Patent Publication No. 44237/
1983. The flow rate in the reactor core should range
from 80 to 120% to maintain the output of the nuclear

25   reactor at 100%.
       According to this embodiment, the inner tube 20
and the outer tube 21 have been so specified that the
condition of Fig. 3A is established in the water rod
19 when the flow rate in the reactor core is smaller

30   than 80% and that the condition of Fig. 3C is
established in the water rod 20 when the flow rate
in the reactor core is 110%. The flow rate of 80%
in the reactor core is the one which corresponds to
the maximum value S_0 of Fig. 2 at which the cooling

35   water is supplied into the water rod 19, and the flow

rate of 110% in the reactor core is the one which
corresponds to the point R of Fig. 2 at which the
cooling water is supplied into the water rod 19.

During the period of up to 70% of both the first
fuel cycle and the second fuel cycle, the flow rate
in the reactor core is maintained at 80% as shown in
Fig. 17(d) and the change in the output of the nuclear
reactor due to the consumption of the core material
is compensated by gradually pulling out the control
rods using a finely-driving control rod driving device.
From 70% of the fuel cycle to the end of the fuel
cycle, the flow rate in the reactor core is gradually
increased from 80% to 120% while halting the operation
of the control rods. With the output of the nuclear
reactor being controlled as described above, the
surplus reactivity in this embodiment is maintained
at a minimum level necessary for criticality for a
predetermined period of time (Fig. 17(b)) at the end
of each of the fuel cycles. Furthermore, the ratio
of hydrogen atom density to uranium atom density
greatly increases toward the end of each of the fuel
cycles (Fig. 17(c)). The core material in the
nuclear fuel material loaded in the reactor core is
consumed in small amounts during the period B of
from the start of the fuel cycle to 70% of the fuel
cycle, and is consumed in large amounts during the
period E of from 70% of the fuel cycle to the end
of the fuel cycle, as shown in Fig. 17(a).

In this embodiment which employs nine water rods
19, the whole water rods occupy 30% of the sectional
area of the coolant path of the fuel assembly 35 as
mentioned above, and the variable range of the average
void fraction of the fuel assembly 35 is increased
by as great as 22.5% owing to the function of nine
water rods 19. In practice, however, to this value

is further added 9% of Fig. 8. Therefore, the nuclear
fuel substances can be very effectively utilized,
the period of a fuel cycle can be markedly extended
for operating the nuclear reactor, and the fuel
5   assembly 35 can be simply constructed.

It is further possible to change the shape of
nine water rods 19 of the fuel assembly 35 (e.g., to
differ the inner diameter of the inner tube 20 of
nine water rods 19) to vary the transition period
10   from the state of Fig. 3A to the state of Fig. 3C.

Figs. 18A to 24 illustrate further embodiments
of the water rod 19 employed for the fuel assembly
10 and the fuel assembly 35.

In the water rod 19A of Figs. 18A and 18B, a
15   coolant ascending tube 40 and a collant descending
tube 41 are coupled together through a coupling tube
42, thereby to form a coolant ascending path 43 and
a coolant descending path 44. The water rod 19A
exhibits the function same as that of the water rod
20   19, but presents an advantage in that the metal has
a small sectional area with respect to the area
occupied by the water rods. In this embodiment, the
coolant delivery port 29 is opened downwardly and
may be affected by the dynamic pressure of the cooling
25   water that flows upwardly in the fuel assembly. In
the water rod 19B of Fig. 19, the lower end of the
descending tube 16 is closed and delivery ports 29
are formed in the side surface of the descending tube
16 so as not to be affected by the dynamic pressure.
30   In the water rod 19C of Fig. 20, the upper end
of the inner tube 20 of the water rod 19 shown in
Fig. 6 is brought into contact with a cover portion
23, and openings 45 are formed at the upper end of
the inner tube 20. The water rod 19C is advantageous
35   in regard to easily supporting the weight of the outer

tube 21.

In the aforementioned water rods, the members constituting the coolant ascending path and the coolant descending path possessed a circular shpae in cross section. The sectional shape, however, needs not be limited to a circle, only, but may be of any shape.

In the water rod 19D shown in Fig. 21, the outer tube 21 of the water rod 19 is replaced by an outer tube 46 that has a nearly rectangular shape in cross section. Reference numeral 47 denotes a spacer that maintains a distance between the inner tube 20 and the outer tube 46, and has the same height as the spacer 22. Compared with the outer cylinder 21 having a circular shape in cross section, this water rod 19D is advantageous in that the sectional area can be windened without disarraying the fuel rods 11.

Furthermore, the number of the coolant ascending path 25 and the number of the coolant descending path 26 need not necessarily be corresponded to be 1 to 1. For instance, a plurality of inner tubes 48 and a single rectangular outer tube 46 may be employed to constitute a water rod 19E that is shown in Fig. 22. In this case the holes of the fuel rod supporting portion 14 of the lower tie plate 13 are arranged maintaining the same pitch as that of the fuel rods.

It needs not be pointed out that the fuel assemblies 10 provided with the water rods of Figs. 18A to 22 instead of the water rod 19, also exhibit the same effects as the fuel assembly provided with the water rod that is shown in Fig. 4.

In the water rod 19F shown in Fig. 23, the outer tube 21A has a length one-half that of the outer tube 21 of the water rod 19, and the delivery ports 29 of the coolant descending path 26 are formed at a

position of a height one-half the whole length of
the fuel assembly in the axial direction. The
coolant descending path 26 has a length one-half
that of the water rod 19. In the water rod 19F, the
difference of static water head decreases between the
coolant ascending path 25 and the coolant descending
path 26 when the flow rate is small, and a maximum
value of pressure differential decreases between the
outlet and the inlet of the water rod 19F. On the
other hand, to the pressure differential on the outer
side of the water rod 19F are added not only the
pressure loss of the fuel rod supporting portion 14
of the lower tie plate 13 but also the pressure loss
of the fuel assembly, so that there easily develops
a pressure differential between the outlet and the
inlet of the water rod. Therefore, the pressure loss
caused by the lower tie plate 13 can be decreased.

Though the water rods were arranged inside the
fuel assembly, the same effects can also be obtained
even when the water rods are arranged outside the
fuel assembly.

In the water rod, the inner tube and the outer
tube need not have the same sectional areas in the
lengthwise direction thereof; i.e., an inner tube 50
whose sectional area changes in the axial direction
may be used as in a water rod 19G of Fig. 24. In
this water rod 19G, the cooling water exists in an
increased amount in the upper portion of the reactor
core when the flow rate is small, when the coolant
descending path 26 is filled with the vapor, and when
the liquid condensed water exists only in the coolant
ascending path 25 that flares upwardly (condition of
Fig. 3A). Outside the water rod 19G, on the other
hand, the cooling water exists in large amounts in
the lower portion, contributing to uniformalizing

the amount of the cooling water in the axial direction
of the fuel assembly. The coolant descending path
26 of the water rod 19G has a length of from the
upper end to the lower end of the fuel pellet-filled
5   region of the fuel assembly in the axial direction
thereof. In the water rod 19G of Fig. 24, the cooling
water ascending path 25 has a sectional area that
continuously changes upwardly. The coolant ascending
path, however, may be divided into two regions having
10   different sectional areas, so that the upper region
will have a sectional area greater than that of the
lower region. The sectional area is the same in the
upper and lower regions of the coolant ascending path
25. The boundary between the two regions of the
15   coolant ascending path 25 is located at a position of
one-half the total length thereof from the lower end
of the fuel pellet region.
        When the fuel assembly shown in Fig. 4 and Table
1 of Japanese Patent Publication No. 29878/1983
20   (Fig. 4 and Table 1 of U.S.P. 4,229,258) is provided
with the water rod 19G and, particularly, with the
coolant ascending path 25 that has different sectional
areas in the upper and lower regions, the difference
of the enrichment (the upper portion has a higher
25   enrichment than the lower portion) in the upper and
lower regions of the fuel assembly can be reduced
owing to the function of the water rod. In the fuel
assembly, the average enrichment is divided into two
regions at a position of one-half the length thereof
30   from the lower end of the fuel pellet-filled region
of the fuel assembly. The boundary is located at a
position of 1/3 to 7/12 of the length thereof in the
axial direction from the lower end of the fuel pellet-
filled region.
35   When the sectional area of the coolant ascending

path 25 is varied in the upper and lower regions as
described above, the position at which the sectional
area changes is set to be the same as the position
at which the enrichment is divided.

5   The fuel assemblies having the water rods 19F
and 19G exhibit the same effects as those of the fuel
assembly 10.

      Fig. 25 illustrates a fuel assembly according
to a further embodiment of the present invention.
10   The fuel assembly 51 of this embodiment is the one
in which the aforementioned water rod 19 is adapted
to the fuel assembly that is shown in Fig. 15 of
Japanese Patent Application No. 126109/1985 (Fig. 15
of Japanese Patent Laid-Open No. 284696/1986; Fig.
15   12 of the corresponding U.S. Appln. Serial No. 871,996
filed June 9, 1986). Described below are the
differences of this embodiment from the aforementioned
fuel assembly 10. The greatest difference is that
the fuel assembly 51 has an orifice 52 arranged in
20   space 15 of the lower tie plate 13, and the inner
tube 20A of the water rod 19A downwardly extends
beyond the orifice 52 penetrating through the fuel
rod supporting portion 14 and the orifice 52. The
water rod 19H is the one in which the inner tube 20
25   of water rod 19 of the fuel assembly 10 shown in
Fig. 7A is replaced by a longer inner tube 20A, and
has the structure same as that of the water rod 19
in other respects. Therefore, the cooling water
inlet port (opening at the lower end of the inner
30   tube 20A) 28 of the water rod 19H is open in space
15 under the orifice 52, and coolant delivery ports
29 at the lower end of the outer tube 21 are located
at a position over the fuel rod supporting portion
14 but under the fuel pellet-filled region of the
35   fuel assembly 51. A coolant ascending path is formed

in the inner tube 20A, and a coolant descending path
is formed between the inner tube 20A and the outer
tube 21. Like the water rod 19, the inverting portion
27 of the water rod 19H is provided at the position

5   of gas plenum 34 of fuel rods 11, i.e., provided at
a position higher than the upper end of the fuel
pellet-filled region of the fuel assembly 51. The
fuel assembly 10 employs a fuel rod supporting
portion 14 of the lower tie plate 13 that serves as

10   a resistance member to produce a pressure differential
between the outlet and the inlet of the water rod.
The fuel assembly 51, however, employs the fuel rod
supporting portion 14 and an orifice 52 as the
resistance member. According to this embodiment,

15   therefore, the pressure differential between the
outlet and the inlet of the water rod becomes greater
than that of the fuel assembly 10.

The orifice 52 constitutes a resistance device.
As shown in Figs. 26 and 27, the orifice 52 consists

20   of a ring 53 and thirteen round rods (or pipes) 54
having a circular shape in cross section that are
mounted in parallel maintaining a distance. Gaps 55
are formed among the neighboring round rods 54 to
constitute coolant paths. Reference numeral 55A

25   denotes a throat portion in which the gaps 55 become
narrowest. Gaps 55 of the orifice 52 gradually
increase from the throat portion 55A toward the
upstream side and the downstream side, and are each
defined by a pair of side walls (side surfaces of

30   the neighboring round rods 54) constituted by
continuous surfaces without corners. The orifice
52 has gaps 54 in a plurality of numbers. The round
rods 54 are resistance members which have a sectional
shape whose size in a direction at right angles with

35   the direction of coolant flow increases gradually

toward the downstream direction (FL) and then decreases gradually.

The ring 53 of orifice 52 is mounted on the inner surface of the lower plenum 13. The orifice 52 is provided at right angles with the axis of the fuel assembly 51. The inner tube 20A of the water rod 19H that penetrates through the fuel rod supporting portion 14, further penetrates through a hole 56 formed in the central round rod 54 of the orifice 52, and downwardly protrudes beyond the orifice 52.

Japanese Patent Application No. 126109/1985 describes that the characteristics shown in Fig. 28 were obtained when the flowability was tested using an orifice mentioned on page 8, lines 5 to 9 and 16 of the specification of this application (page 3, upper right column, line 5 to lower left column, line 16 of Japanese Patent Laid-Open No. 284696/1986; page 9, line 11 to page 11, line 2 of the specification of U.S. Appln. Serial No. 871,996), that was constructed in a small size. In Fig. 28, the abscissa represents the Reynolds number Re and the ordinate represents the orifice fraction Kor. The orifice fraction Kor of the above small orifice becomes about 77 near at $Re = 13 \times 10^4$ that corresponds to the naturally circulating condition (point B of Fig. 29) of the boiling-water reactor, and becomes about 60 at $Re = 45 \times 10^4$ that corresponds to 100% reactor output (point C of Fig. 29) of the boiling-water reactor. The orifice fraction Kor at the point C of Fig. 29 is lower by about 22% than that at the point B of Fig. 29. Therefore, the pressure loss at the point C is smaller by about 22% than that at the point B. The orifice fraction Kor of the orifice 5 is about 77 which remains nearly constant over a range of from $Re = 13 \times 10^4$ to $Re = 30 \times 10^4$, and gradually

decreases when Re becomes greater than 30×10^4.
The point of Re = 30×10^4 corresponds to the moment
of when the flow rate in the core is about 60% in
Fig. 29.

5   The reason why the characteristics shown in
Fig. 28 are obtained has been taught on page 10,
line 17 to page 12, line 18, and in Figs. 27 and 28
of the specification of Japanese Patent Application
No. 126109/1985 page 3, lower right column, line 17

10   to page 4, upper right column, line 18 and Figs. 27
and 28 of Japanese Patent Laid-Open No. 284696/1986;
page 11, line 25 to page 14, line 5, and Figs. 9 and
10 of the specification of U.S. Appln. Serial No.
871,996). The specification of Japanese Patent

15   Application No. 126109/1985 describes on page 13,
lines 8 to 15 and in Figs. 29(A) to 29(F) (page 4,
lower left column, lines 8 to 15, and Figs. 29(A) to
29(F) of Japanese Patent Laid-Open No. 284,696/1986;
page 14, lines 15 to 25, and Figs. 11A to 11F of the

20   specification of U.S. Appln. Serial No. 871,996) that
the bars having any other sectional shape may be
used instead of the round rods.

The orifice used in this embodiment has a
pressure loss transition region in which the pressure

25   loss decreases for the flow rate of 80 to 110% in
the reactor core.

As the flow rate in the reactor core increases
and the Reynolds number Re exceeds the critical
Reynolds number Rec, the pressure loss of the orifice

30   52 starts to decrease as shown in Fig. 28. At a
moment when the reactor output is 100% (point C in
Fig. 29), the pressure loss decreases remarkably
compared with the pressure loss at the moment of
point D. Using the fuel assembly 51 of this embodiment,

35   therefore, the flow rate of the cooling water delivered

from the recirculation pump at the point C of Fig.
29 is smaller, by an amount that corresponds to the
reduction of pressure loss of the orifice 52, than
the flow rate of the cooling water delivered from the

5   recirculation pump at the point C in Fig. 29 in the
boiling-water reactor loaded with the fuel assembly
10.   In this embodiment, the capacity of the
recirculation pump is equal to that of the pump used
in the water-boiling reactor loaded with the fuel

10   assembly 10.   Using the fuel assembly 51 of this
embodiment, therefore, the flow rate in the reactor
core increases more than that of the prior art after
the point C of Fig. 29 is reached.   That is, in the
boiling-water reactor loaded with the fuel assembly

15   10, the flow rate in the reactor core of 120% was
an upper limit.   In the boiling-water reactor loaded
with the fuel assembly 51, however, the flow rate
in the reactor core can be increased in excess of
120%.   By providing the fuel assembly 51 of this

20   embodiment, therefore, the output of the nuclear
reactor can be controlled over a wide range by
controlling the flow rate in the reactor core.

In case the recirculation pump has tripped when
the nuclear reactor is in operation at 100% output,

25   the flow rate in the reactor core decreases and the
cooling water in the reactor core is placed under
the naturally circulating condition.   Accompanying
the reduction of the flow rate in the reactor core,
the output of the nuclear reactor decreases along a

30   straight line BC in Fig. 29 down to the point B.
Thus, as the flow rate in the core is placed under
the naturally circulating condition, the orifice
fraction Kor of the orifice 52 increases.   Therefore,
the fuel assembly of this embodiment prevents the

35   flow rate in the reactor core from losing stability

when it is placed under the naturally circulating
condition (operation is prevented from plunging into
the unstable region of Fig. 29).

5   The water rod 19H of the fuel assembly 51 of this
embodiment is so constituted that the condition of
Fig. 3A takes place when the flow rate is smaller
than 100% in the reactor core and that the condition
of Fig. 3D takes place when the flow rate is greater
than 110% in the reactor core. Therefore, the water
10   rod 19H of the fuel assembly 51 works in the same way
as the water rod 19 of the fuel assembly 10 mentioned
earlier, and the fuel assembly 51 produces the same
effects as the fuel assembly 10.

Furthermore, the fuel assembly 51 which is
15   provided with the orifice 52 makes it possible to
vary the void fraction over a wide range of flow
rate in the reactor core compared with the fuel
assembly 10. Since the pressure loss by the orifice
52 decreases (Fig. 28), the flow rate in the reactor
20   core can be varied greatly to change the flow in
the water rod 19H. This will be explained in
conjunction with Fig. 30, wherein the left side shows
the flow condition of cooling water in a region outside
the water rod 19H and the right side shows the flow
25   condition of cooling water in the water rod 19H.
On the left side of Fig. 30, a curve K_1 of a solid
line represents flow characteristics of the fuel
assembly having the fuel rod supporting portion 14
without orifice 52, and a curve K_2 of a broken line
30   represents flow characteristics of the fuel assembly
of when it is presumed that the fuel rod supporting
portion 14 is replaced by the orifice 52. Symbol
ΔP of Fig. 30 represents a width in which the
pressure differential of the fuel assembly changes
35   between the coolant inlet port 28 and the coolant

delivery port 29 of the water rod 19H. In other
words, ΔP represents a width in which the pressure
differential changes between the coolant inlet
port 28 and the coolant delivery port 29 of the

5 water rod 19H. To produce the variable width ΔP,
the flow rate of cooling water that flows through
the fuel assembly is increased by ΔF_1 on the curve
K_1 and is increased by ΔF_2 on the curve K_2. By
using the orifice 52 of which the pressure loss

10 decreases with the increase in the flow rate in
the reactor core, as described above, the range
increases in which the flow rate in the reactor core
varies to obtain the same range of pressure
differential change as that of when the orifice 52

15 is not employed. This is advantageous not only
when the spectrum-shift operation is carried out
but also when the output of the nuclear reactor is
controlled relying upon the flow rate in the reactor
core.

20 When the pressure differential characteristics
in the water rod has a distinct maximum value and a
distinct minimum value as represented by a curve on
the right side of Fig. 30, the transition is started
along the characteristics curve on the right side of

25 the maximum value when the maximum value is exceeded
even by a slightest amount, and it is not allowed
to flatten the pressure differential between the
outlet and the inlet of the water rod. However,
when the pressure differential between the outlet

30 and the inlet of the water rod changes flatly as
shown in Fig. 31, the orifice 52 is effective to
flatten the flow rate in the reactor core vs. void
fraction characteristics on the right side of the
maximum value. Fig. 31 illustrates characteristics

35 of the water rod 19 (Fig. 7A) which is constituted

using an outer tube 21 having an inner diameter of
20 mm and an inner tube 20 having an outer diameter
of 14 mm and an inner diameter of 12 mm.

5   As described above, the fuel assembly 51 provided
with the water rod 19H and the orifice 52 produces
a variety of effects. Furthermore, the fuel assembly
51 helps achieve the effects as described below.
That is, in the boiling-water reactor equipped with
the fuel assembly 51 of this embodiment, reduction
10 in the output of the nuclear reactor due to the
consumption of core material is compensated by
increasing the flow rate in the reactor core over a
range of 80% to 100% in which the flow rate in the
reactor core changes. Since the fuel assembly 51 is
15 provided with the orifice 52, the pressure differential
between the outlet and the inlet of the water rod
19H varies less sensitively relative to fluctuation
in the flow rate in the reactor core. This also
contributes to increasing the range in which the flow
20 rate in the reactor core varies to compensate the
reduction of reactor output due to the consumption
of the core material.

A further embodiment of the present invention
employing the orifice 52 will be described in
25 conjunction with Fig. 32. In a fuel assembly 57 of
this embodiment, the water rod 19H employed in the
fuel assembly 51 is replaced by a water rod 19I which
consists of an inner tube 20A and an outer tube 21B.
In other respects, the structure is the same as that
30 of the fuel assembly 51. Further, the water rod 19I
has the same structure as the water rod 19, except
that the inner tube 20A and the outer tube 21B are
longer than the inner tube 20 and the outer tube 21
of the water rod 19 of Fig. 7A. The outer tube 21B
35 penetrates through the fuel rod supporting portion

14 to reach the space 15, but does not penetrate
through the orifice 52. Hence, coolant delivery
ports 29 formed at the lower end of the outer tube
21B are open in space 15 between the fuel rod
5   supporting portion 14 and the orifice 52. The fuel
assembly 57 uses the orifice 52 as a resistance
member that produces a pressure differential between
the outlet and the inlet of the water rod 19I. The
fuel rod supporting portion 14 of this embodiment
10   does not serve as the above-mentioned resistance
member. Therefore, the pressure differential produced
across the outlet and the inlet of the water rod 19I
becomes smaller than the pressure differential
produced thereacross of the water rod 19H.
15   However, the fuel assembly 57 provided with the
water rod 19H and the orifice 52 exhibits the same
effects as those of the fuel assembly 51 mentioned
earlier..
         In the fuel assembly 57, the cooling water
20   delivered from the coolant delivery ports 29 of the
water rod 19I is supplied into space among the fuel
rods 11 via the fuel rod supporting portion 14.
Therefore, the flow rate of cooling water that passes
through the fuel rod supporting portion 14 becomes
25   greater than that of the fuel assembly 51 and the
fuel assembly 10, and the pressure loss increases
in the fuel rod supporting portion 14 compared with
the fuel assembly and the fuel assembly 10. Furthermore,
the fuel assembly 57 is cumbersome to fabricate
30   compared with the fuel assembly 51. In the fuel
assembly 57, on the other hand, the pressure
differential is generated by the orifice 52 only to
flow the cooling water into the water rod 19I as
mentioned earlier. Therefore, the width in which the
35   pressure loss decreases becomes relatively great

compared with that of the fuel assembly 51. Therefore, the range increases in which the flow rate in the reactor core can be changed.

The water rods shown in Figs. 18A to 24 and the
5   structure mentioned in relation to these water rods can be adapted to the fuel assemblies 51 and 57, as a matter of course.

When there is no need of changing the pressure loss unlike the orifice 52, a generally employed
10   orifice plate having a round hole may be used instead of the orifice 52 of the fuel assembly 51 or 57.

Finally, the structure of the boiling-water reactor in which the above-mentioned fuel assembly is loaded will now be described in conjunction with
15   Fig. 33.

A boiling-water reactor 60 has a reactor pressure vessel 61, a recirculation pump 70 and a reactor core 67 loaded with the fuel assembly 10. A reactor core shroud 62 is arranged in the reactor pressure
20   vessel 61 and is mounted therein. Jet pumps 68 are arranged between the reactor pressure vessel 61 and the reactor core shroud 62. A lower support plate 63 of the reactor core is mounted on the lower end of the reactor core shroud 62 and is arranged therein.
25   A plurality of fuel support metal fittings 65 penetrate through the lower support plate 63 of the reactor core and are installed on the lower support plate 63 of the reactor core. Upper lattice plates 64 are arranged in the reactor core shroud 62 and are
30   mounted thereon. A plurality of control rod guide tubes 72 are installed in a lower plenum 71 under the lower support plate 63 of the reactor core. Housings 74 of control rod drive devices are mounted on the bottom of the reactor pressure vessel 61.
35   A recirculation conduit 69 which communicates the

reactor pressure vessel 61 with the reactor core
shroud 62 is open at the upper end of the jet pumps
68. The recirculation conduit 69 is provided with
the recirculation pump 70. Control rods 73 are
5   arranged in the control rod guide tubes 72, and are
linked to control rod driving devices (not shown)
installed in the housings 74 of the control rod drive
devices. The lower tie plates 13 of the fuel assembly
10 are inserted in and are held by the fuel support
10   metal fittings 65, and the upper ends thereof are
supported by the upper lattice plates 64. Being
driven by the control rod drive devices, the control
rods 73 are inserted among the fuel assemblies 10
penetrating through the fuel support metal fittings
15   65.

The cooling water is supplied into the reactor
core 67 as described below. That is, the recirculation
pump 70 is driven, and the cooling water between the
reactor pressure vessel 61 and the reactor core
20   shroud 62 is injected to the upper end 35 of jet pump
68 through the recirculation conduit 69. The cooling
water between the reactor pressure vessel 31 and the
reactor core shroud 32 is further intaken by the jet
pump 35 as the cooling water is injected. The cooling
25   water delivered from the jet pump 35 flows into the
lower plenum 71 and into the cooling water paths 66
of the fuel support metal fittings 65, and is
supplied into the fuel assembly 10 via the lower tie
plate 13.
30   When the nuclear reactor is producing the output
of a low level, the control rods 72 are pulled out
from the reactor core to increase the output of the
nuclear reactor. The output of a high level of the
nuclear reactor can be controlled by changing the
35   number of revolutions of the recirculation pump 70

and by increasing or decreasing the flow rate in the
reactor core.

By pulling out the control rods and by adjusting
the flow rate in the reactor core, the nuclear reactor
5 produces a rated 100% output with a flow rate in the
reactor core of 80%. The operation for compensating
the decrease of reactor output due to the consumption
of the core material and the operation for shifting
the flow condition in the water rod 19 from the
10 condition of Fig. 3A to the condition of Fig. 3C,
are performed by increasing the flow rate in the
reactor core, i.e., by increasing the number of
revolutions of the recirculation pump 70. With the
recirculation pump running at a speed that produces
15 the flow rate of smaller than 100% in the reactor
core, the condition of Fig. 3A is established in the
water rod 19 whereby the vapor is built up in the
coolant descending path 26. With the recirculation
pump running at a speed that produces the flow rate
20 of greater than 110% in the reactor core, the condition
of Fig. 3C is established in the water rod 19, and
no vapor is built up. It can therefore be said that
the recirculation pump 70 serves as means that controls
the accumulating amount of voids (vapor) in the water
25 rod 19.

The fuel assembly 35, 51 or 57 may be loaded in
the reactor core 67 instead of the fuel assembly 10.

Furthermore, the recirculation pump 70 may be
replaced by an internal pump that is mounted in the
30 reactor pressure vessel 61.

According to the present invention, the range
greatly increases in which the average void fraction
of the fuel assembly changes relying upon a simple
structure, and the nuclear fuel substances can be
35 utilized very efficiently.